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Bibliometric Analysis on Smart Self-Healing Nanocoating for 316L Stainless Steel Biomedical Implants

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Abstract: This study presents a bibliometric analysis of research on smart self-healing nanocoatings for 316L stainless steel biomedical implants between 2015 and 2025. The aim is to explore publication trends, identify leading contributors, and uncover gaps in knowledge within this emerging field. A total of 237 documents were collected from the Scopus database using a well-defined search strategy. Performance analysis and science mapping techniques were applied using VOSviewer, Bibliometrix, and supporting tools. The results show a consistent increase in publication volume, with a notable rise after 2020, suggesting growing interest in self-healing materials for biomedical applications. The most common document types are research articles (44.3%) and reviews (38%), with most publications falling under materials science, engineering, and chemistry. India and China lead in publication count, while countries like Canada and Australia demonstrate high average citation impact. Keywords like "corrosion," "biocompatibility," and "hydroxyapatite" dominate the field, while "self-healing" appears infrequently, indicating an underexplored area. Experimental focus remains largely on in vitro studies, with limited in vivo or simulation-based research. Most coatings are tested in lab settings, and only a few studies move toward biological or computational validations. This paper highlights the need for broader interdisciplinary efforts and deeper translation of lab findings into real biomedical applications.

Keywords: Self-healing nanocoatings, 316l stainless steel, Biomedical implants, Bibliometric analysis, Corrosion protection

Introduction

Biomedical implants have changed modern medicine by enabling the replacement of damaged tissues and organs, eventually increasing patients' quality of life (Coelho et al., 2018). Among different metallic biomaterials used for

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implants, 316L stainless steel has gotten a significant position due to its comparatively inexpensive cost, good mechanical qualities, and acceptable biocompatibility (Badhai et al., 2023). Despite these advantages, the efficacy and lifetime of 316L stainless steel implants are considerably limited by their susceptibility to corrosion in the complex physiological milieu of the human body (Kibambe et al., 2023). This corrosion process not only leads to the destruction of the implant but also results in the release of potentially poisonous metal ions, which can cause unfavorable tissue reactions, implant failure, and ultimately need revision procedures (Al-Mamun et al., 2020; Kibambe et al., 2023).

For metallic implants, the human body is an aggressive environment because of things like proteins, enzymes, chloride ions, and different pH levels, all of which speed up the corrosion process (Gherasim et al., 2021; Montazerian et al., 2022). Specifically, pitting corrosion is encouraged by the presence of chloride ions in bodily fluids, but proteins can either hinder or speed up corrosion based on certain circumstances (Deepa et al., 2022; Gopal Krishna et al., 2023). The corrosion landscape is further complicated by microbially driven corrosion that results from growth on implant surfaces (Pua et al., 2024). These issues are especially important for 316L stainless steel implants, which are susceptible to localized corrosion over time when exposed to the physiological environment, even when they have chromium to generate a passive oxide layer (Liu et al., 2016).

The use of passive coatings, surface treatments like nitriding or carburizing, and alloying with elements like molybdenum have all been used historically to increase the corrosion resistance of 316L stainless steel implants (Dahmani, 2024). However, these traditional techniques have drawbacks, especially when it comes to long-term protection, since they usually offer a static barrier that exposes the underlying metal to corrosive media after it is broken (Zhang et al., 2020). Smart self-healing nanocoatings have appeared as a possible alternative for next-generation implants because of this constraint, which has prompted researchers to investigate more sophisticated approaches (Katta & Nalliyan, 2019).

Self-healing materials show a change in thinking in the design of materials, motivated by biological systems that could automatically show and fix damage (Xiong et al., 2019). Self-healing qualities in protective coatings for biomedical implants can independently restore barrier properties following damage, significantly increasing the implant's service life and lowering the risk of problems(Xiong et al., 2019; H. Zhang et al., 2024). By allowing more precise control over healing mechanisms, increased mechanical qualities, and the addition of new capabilities like antibacterial activity, nanotechnology has significantly improved the effectiveness of these self-healing systems (Zhang et al., 2024).

Over the past ten years, several methods for creating self-healing nanocoatings for metallic implants have been discovered. Typically, extrinsic self-healing systems encapsulate healing chemicals in nano- or microcontainers that, when damaged, release their contents to restore the coating (Xiong et al., 2019). Halloysite nanotubes, mesoporous silica nanoparticles, and more intricate systems like layer-by-layer assemblies and stimuli-responsive polymeric capsules are examples of these containers (Khaled & Santhiya, 2024). The actual healing agents could be pH buffers, corrosion inhibitors, or polymerizable substances that create a fresh barrier (Xiong et al., 2019). As an alternative, intrinsic self-healing coatings offer recurrent healing capabilities without the need of encapsulated agents by relying on reversible chemical bonds or physical interactions that can be repaired after being broken (Zhao et al., 2023).

Recent developments in materials science, nanotechnology, and surface engineering have fueled the explosive expansion of the smart self-healing nanocoatings market for 316L stainless steel (Li et al., 2025). Although this expanding field of study has yielded many creative methods, it has also made it more difficult to keep track of significant advancements, spot research patterns, and spot new prospects. It is more difficult to summarize the current state of knowledge and pinpoint interesting avenues for future research because different studies use different method, materials, and evaluation techniques.

Given these challenges, there is a clear need for a comprehensive assessment of the research landscape in this field. Bibliometric analysis offers a powerful tool for this purpose, enabling the quantitative evaluation of research outputs and the identification of patterns, trends, and relationships within scientific literature. By applying bibliometric techniques to the literature on self-healing nanocoatings for 316L stainless steel implants, it becomes possible to map the intellectual structure of the field, find key research clusters, and highlight both well-established areas and emerging frontiers (Hoang, 2025).

Prior bibliometric analyses have examined more general topics associated with our area of interest. For example, Zhu et al. (2022) reviewed biomedical applications of two-dimensional nanomaterials over the last decade, while Kumar (2021) performed a bibliometric study of studies on corrosion-resistant coatings for Titanium Implants.

However, as far as we are aware, no thorough bibliometric analysis has been conducted, especially on smart self-healing nanocoatings for biomedical implants made of 316L stainless steel. This is a big gap since a study like this would give scholars, funding organizations, and industry stakeholders interested in this niche but quickly expanding field useful information.

There are special potential and challenges at the intersection of materials science, corrosion engineering, and biomedical research that call for careful consideration. Additionally, transferring cutting-edge coating technologies from lab to clinical settings requires negotiating scale-up difficulties, regulatory concerns, and long-term performance evaluations that might not be sufficiently represented in more comprehensive analyses. This study intends to offer a focused evaluation of research trends, partnerships, and knowledge gaps in this crucial field by concentrating especially on smart self-healing nanocoatings for 316L stainless steel biomedical implants.

Research on self-healing nanocoatings for 316L stainless steel has been influenced by a number of noteworthy developments in recent years. According to Xiong et al. (2019), laboratory investigations have proved encouraging outcomes in the creation of pH-responsive nanocontainers that release corrosion inhibitors precisely in response to the acidic environment formed during corrosion processes. Comparably, multilayer coatings that combine controlled drug release with self-healing qualities have been a popular tactic to address infection and corrosion threats at the same time (Gergely, 2018; Kumar et al., 2017). Because of their barrier qualities and capacity to include functional groups that promote healing processes, graphene oxide and other two-dimensional nanomaterials have also garnered a lot of interest as parts of self-healing systems (Zhu et al., 2022).

Even with these developments, there are still many obstacles to overcome before these technologies may be used in therapeutic settings. Critical issues for future research include the possible toxicity of released healing agents, the long-term durability of nanocoatings in physiological settings, and the effect of sterilizing procedures on coating performance (Al-Mamun et al., 2020; Yu et al., 2025). To aid in clinical translation, it is also necessary to examine how well these sophisticated coating systems interact with current production procedures and medical device regulatory frameworks.

A thorough understanding of the state of research is necessary to understand these issues and pinpoint possible avenues for future investigation. A bibliometric analysis can give this overview and help inform strategic choices about future research goals by mapping the literature's publishing trends, collaboration networks, and subject focuses (Hoang, 2025). Such a study can assist in identifying uncharted territory, possible areas of cooperation, and new trends that could influence the development of self-healing nanocoatings for biomedical implants in the future.

Another developing area in this subject is the combination of artificial intelligence (AI) and machine learning (ML) approaches, which may be used for everything from coating performance prediction to the improvement of healing mechanisms in particular scenarios (Vasudev & Mehta, 2024). Comparably, the idea of theragnostic coatings, which combine therapeutic and diagnostic properties, presents intriguing prospects for next-generation implants that can monitor implant status, react to environmental changes, and prevent corrosion.

The goal of this work is to present a bibliometric analysis of studies on smart self-healing nanocoatings for biomedical implants made of 316L stainless steel that were published between 2015 and 2025. We want to map the intellectual landscape of this discipline and find both established research areas and rising frontiers by looking at publication trends, author partnerships, geographical distributions, topic focuses, and citation patterns. We also hope to show any gaps between clinical translation and technological advancement by examining the methodological strategies used in numerous studies, especially regarding in vitro versus in vivo testing. We expect that our study will yield insightful information that will help direct future studies and speed up the creation of safer, more resilient, and more effective coatings for biomedical implants.

Methodology

Bibliometric Analysis Framework

A quantitative approach that uses statistical methods to examine academic literature, bibliometric analysis offers insights into knowledge structures, research trends, and collaboration patterns within a particular subject (Donthu et al., 2021). This method is especially useful for mapping quickly changing fields of study where conventional qualitative evaluations would find it difficult to fully capture the range of advancements (Hoang, 2025; Mutafi et al., 2025). To present a comprehensive overview of research on smart self-healing nanocoatings for 316L stainless steel biomedical implants, we used a thorough bibliometric framework for this study that combines performance analysis and scientific mapping methodologies.

Evaluating productivity metrics, including impact indicators, citation trends, and publication counts, is the main goal of performance analysis. This part of our approach aids in finding significant studies, important authors, and patterns in the output of research over time. On the other side, science mapping uses methods like keyword co-occurrence analysis, bibliographic coupling, and co-citation analysis to investigate the conceptual, intellectual, and social structures of the study field. This method shows links between research themes, research front evolution, and field collaboration networks.

Data Sources and Search Strategy

To ensure comprehensive coverage of the research landscape, we collected bibliographic data from a major academic database, which is the Scopus database. This database was selected for its extensive coverage of peer-reviewed literature in materials science, engineering, and both mechanical and biomedical research. The search was conducted on April 22, 2025, covering publications from January 1, 2015, to April 22, 2025.
The search strategy was carefully designed to capture relevant publications while minimizing noise. After several iterations and testing, the following search query was completed for both databases, with proper syntax adaptations for each:

("self-healing coating*" OR "smart coating*") AND ("nanocoating*" OR "nano-coating*" OR "nanocomposite coating*") AND ("316L stainless steel" OR "AISI 316L" OR "SS 316L") AND ("corrosion resistance" OR "corrosion protection" OR "anti-corrosion") AND ("biomedical implant*" OR "orthopedic implant*" OR "medical implant*"), Figure 1 illustrates the data collection process.

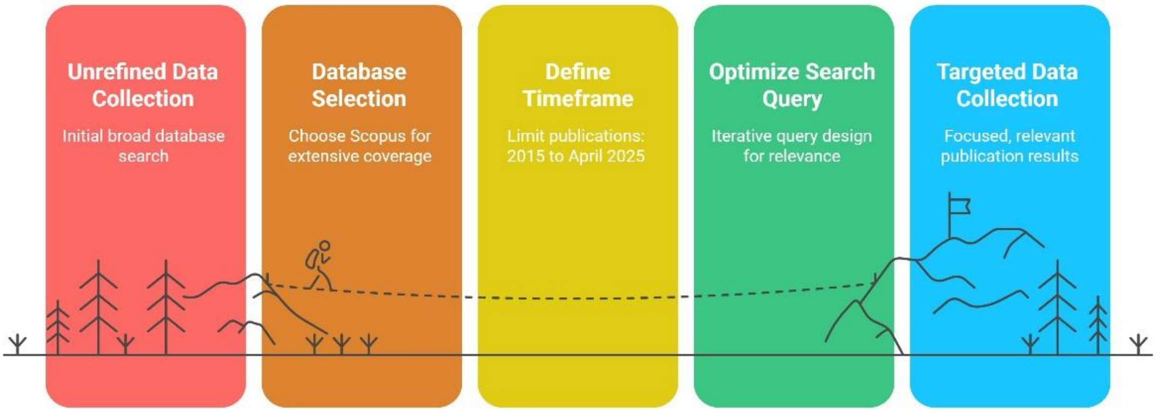

Figure 1. Visual representation of the data collection process, outlining stages from initial database search to refined publication selection.

Bibliometric Analysis Methods

Descriptive bibliometrics and network analysis approaches were employed to provide a thorough evaluation of the research environment after the first search produced 237 papers. The specific techniques listed below were used:

Analysis of Performance:

- Trends in publications: Analysis of growth rates and annual publication counts
- Analysis of citations: Citation distribution and high-citation paper identification
- Analysis of the sources: H-Index, impact factor analysis, and journal productivity
- Productivity of the author: Using Lotka's law to identify prolific authors
- Distribution by geography: Impact of citations and publication counts at the national level of science.

Mapping:

- Analyzing co-authorship networks: Charting author and national collaboration trends
- Co-occurrence network analysis: Using keyword co-occurrence to find study themes.
- Visualizing temporal overlays: Monitoring how research subjects change throughout time.
- Analyzing co-citation networks: Examining scholarly frameworks and significant references

Visualization and Analysis Tools

Several specialized software tools were employed for data analysis and visualization:

1. *VOSviewer (version 1.6.20):* Used for creating and visualizing bibliometric networks, including co-authorship, co-occurrence, and co-citation networks. This tool applies to the VOS mapping technique, which positions items in a two-dimensional space such that the distance between any two items reflects their similarity.
2. *Bibliometrix R-package (version 4.1.1):* Employed for comprehensive bibliometric analysis.
3. *Microsoft Excel:* Utilized for basic statistical analysis.
4. *Canva and Napkin AI:* Creation of descriptive charts and figures

In order to guarantee interpretability and clarity, the visualization parameters were meticulously adjusted. We used clustering algorithms and suitable normalization techniques for network visualizations in order to find cohesive groups. The distribution of values in our dataset was used to establish minimum thresholds for inclusion in networks in order to strike a compromise between readability and comprehensiveness.

Analysis of Research Focus

In order to better understand the present status of research, we introduced several fundamental classifications to enhance bibliometric analysis. Deciding whether publications concentrated on in vitro or in vivo testing was one aspect of this. To compare the quantity of study conducted in each field, we grouped the papers by scanning keywords and abstracts (with the help of ChatGPT at this point). We also used the popular keyword searches to find papers that discussed standard compliance or regulatory topics. However, to give you a sense of how far technology has come, we classified the publications broadly according to their level of technological readiness (from early-stage research to more advanced phases).

These steps helped highlight trends in literature and gave a general view of where most studies are focused, what stages have been reached, and where possible gaps still exist in the development of smart self-healing nanocoatings for biomedical implants.

Results and Discussion

Publication Trends and Growth

The analysis of publication trends reveals a steady growth in research output on smart self-healing nanocoatings for 316L stainless steel biomedical implants over the past decade. Figure 2 illustrates the growth of publications from 2015 to early 2025, showing a consistent upward trajectory with some notable acceleration points. Only four papers were published on this subject in 2015, as shown in Figure 2, proving that it was still in its infancy. Growth over the next years was consistent but slow, ranging from 2 to 9 publications per year between 2016 and 2019. This period most likely reflected the foundational stage, when the researchers were only beginning to investigate the subject. 2020 saw a notable uptick, reaching 18 publications, which signaled a sea change and increased interest and funding for the field. Despite a minor decline to 15 documents in 2021, there was a significant increase in the number of papers in the following years, reaching 24 in 2022 and 31 in 2023.

With 40 papers, 2024 was the highest year, showing the field's increasing momentum and recognition of its importance, particularly in the fields of materials science and biomedicine. Twenty papers had been registered as of April of 2025, indicating that the upward trend is probably going to continue or possibly surpass that of the previous year.

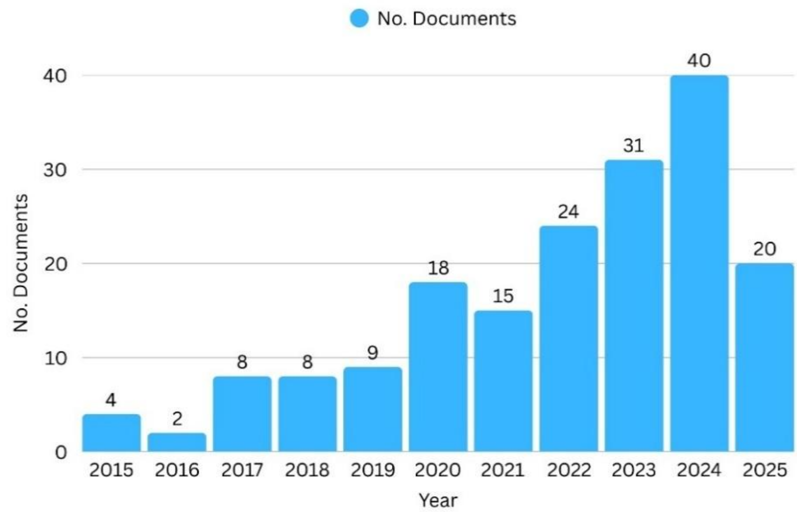

Figure 2. Annual growth in publication volume from 2015 to early 2025 based on the number of indexed documents.

Several things could have an impact on this publication pattern:

- Developments in self-healing nanoparticles and smart coatings
- Research into biomedical implants and infection-resistant surfaces has increased since the epidemic.
- More financing and cross-disciplinary cooperation between biomedical engineering and materials science

The compound annual growth rate (CAGR) over the 10-year period is approximately 23.5%, which significantly exceeds the general growth rate in materials science research (typically around 8–10%). This differential growth rate underscores the increasing importance of research interest in smart self-healing nanocoatings for biomedical applications.

Author Collaboration Network Analysis

To better understand the collaborative structure within this research field, an author collaboration network analysis was conducted. This method reveals the patterns of collaboration among authors and helps identify key contributors, research clusters, and potential interdisciplinary links.

Author Collaboration Network Mapping

A co-authorship network visualization map created with VOSviewer is shown in Figure 3. Individual authors are represented by each node, and co-authorship ties are shown by the lines that connect them according to the articles that are part of the dataset. The thickness of the connecting lines indicates the degree of author collaboration (i.e., the number of co-authored articles), while the size of the nodes indicates the number of publications credited to each author. The network is divided into three distinct clusters, each represented by a different color:

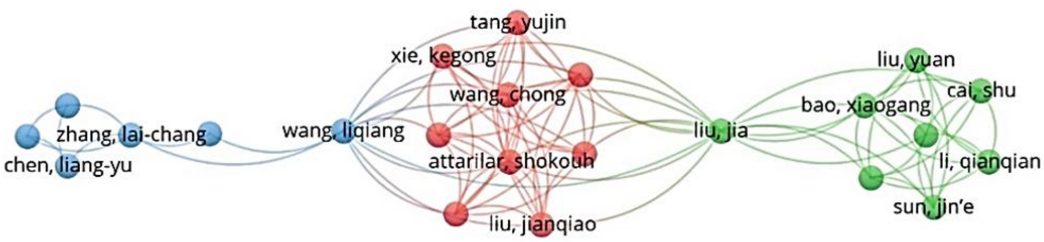

Figure 3. Co-authorship network visualization map generated using VOSviewer.

1. The largest and most connected group is the red cluster, which is situated in the middle of the network. A well-established research team or closely cooperating group working diligently on a common subtopic within the larger field is suggested by the key people in this cluster and the strong internal links within this group.
2. A relatively independent research group with sporadic external collaborations, perhaps from a different institution or sub-discipline, is indicated by the green cluster on the right side of the map, which exhibits strong internal collaboration but seems to be less closely connected to the central (red) cluster.
3. Despite being smaller, the blue cluster on the left appears to be working with the central cluster on specific projects or subjects because of its obvious internal connections and connection to the red cluster through Wang, Liqiang.

Bridging authors, who connect otherwise disparate clusters, are of special interest. These people have the potential to be crucial in promoting multidisciplinary cooperation and knowledge sharing throughout research teams. This network illustrates the dynamics and structure of cooperation in this area of study, indicating that although there are several core teams, intergroup relationships are also becoming more and more common.

Most Productive Authors

In the entire 237 papers, there are 935 writers and co-authors, with 208 serving as first authors. Figure 4 displays the distribution of authors who collaborated on papers. This dataset's authorship distribution is consistent with Lotka's Law (Kumar et al., 2024), which states that a significant percentage of researchers only publish one paper while a much smaller percentage produce multiple publication.

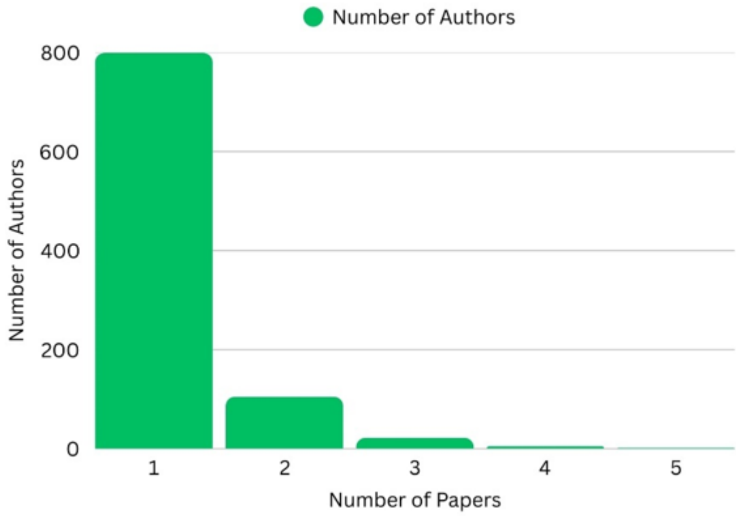

Figure 4. Distribution of the authors that collaborated in papers.

In this case, as the graph in Figure 4 illustrates:

- 799 authors have published only one paper.
- 105 authors have published two papers.
- 22 authors have published three papers.
- 5 authors have published four papers.
- 2 authors have published five papers.
- and 2 authors have published six papers.

The typical Lotka distribution, in which the number of authors rapidly declines as the number of articles per author rises, is reflected in this inverse-square pattern. The findings prove that while most writers contribute with only one publication, a tiny group of prolific authors account for most of the research productivity. Key contributions to the field were determined using the author productivity analysis based on the influence of citations and the quantity of publications. The top 10 most productive writers are listed in Table 1, together with information on their institutional affiliations, total publications, and total citations.

Table 1. Top 10 most productive authors in the field based on publication output and citation count (2015–2025).

Author	Number of Papers	Total Citations	Affiliation
Liu	6	553	Tianjin University - China
Dorozhkin	6	333	M.V. Lomonosov Moscow State University - Russian Federation
Li	5	243	University of Shanghai for Science and Technology - China
Kumar	5	5	Deenbandhu Chhotu Ram University of Science and Technology - India
Kumar	4	176	King Fahd University of Petroleum & Minerals (KFUPM) - Saudi Arabia
Li.	4	453	Shanghai Institute of Technology - China
Chen.	4	146	Nanjing University of Aeronautics and Astronautics - Australia
Xu	4	53	Nanjing University of Aeronautics and Astronautics - Australia
Kumar	4	68	University of Delhi, India
Ramakrishna	3	112	Babol Noshirvani University of Technology - Singapore

According to the study in Table 1, the most productive author is Liu Y. from Tianjin University in China, with six publications and 553 citations. Dorozhkin from M.V. Lomonosov Moscow State University in the Russian Federation comes in second with six publications and 333 citations. It is important to note that, according to the ratio of citations per number of papers in this subject, Li Y. from Shanghai Institute of Technology in China is the most productive author with 453 citations from 4 publications.

Country Analysis

The VOSviewer tool is also used to evaluate contributions from around the world. Only 16 of the 58 nations that made contributions to this topic were able to meet the stringent requirements of having at least five documents and ten citations. illustrating the analysis's selective nature. Figure 5's country co-authorship network map serves as an example of the patterns of international collaboration in this field of study. Each node represents a country, and the size of the node reflects the impact of its citations. The linkages (edges) between countries indicate co-authored papers; longer lines indicate more collaborative relationships.

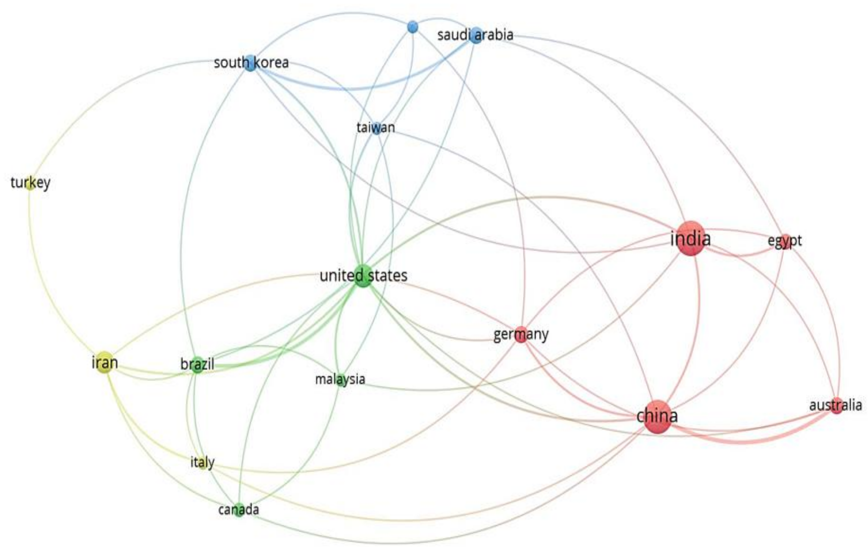

Figure 5. Country co-authorship network map illustrating international collaboration patterns in the field from 2015 to 2025.

Geographic Distribution of Research

The geographic distribution of research on smart self-healing nanocoatings for biomedical implants made of 316L stainless steel is revealed by the study of nation contributions. Figure 6 displays a global map depiction of research activity, and Table 2 lists the top 10 nations by publication output and citation count.

Table 2. Top 10 countries ranked by publication output, citation count, and share of total publications (2015–2025).

Country	Documents	No. Of Citations	% of All Publications
India	61	885	18.54
China	52	2333	15.81
United States	22	589	6.69
Iran	20	595	6.08
South Korea	10	262	3.04
Brazil	10	546	3.04
Saudi Arabia	10	603	3.04
Australia	9	685	2.74
Germany	9	522	2.74
Canada	6	651	1.82

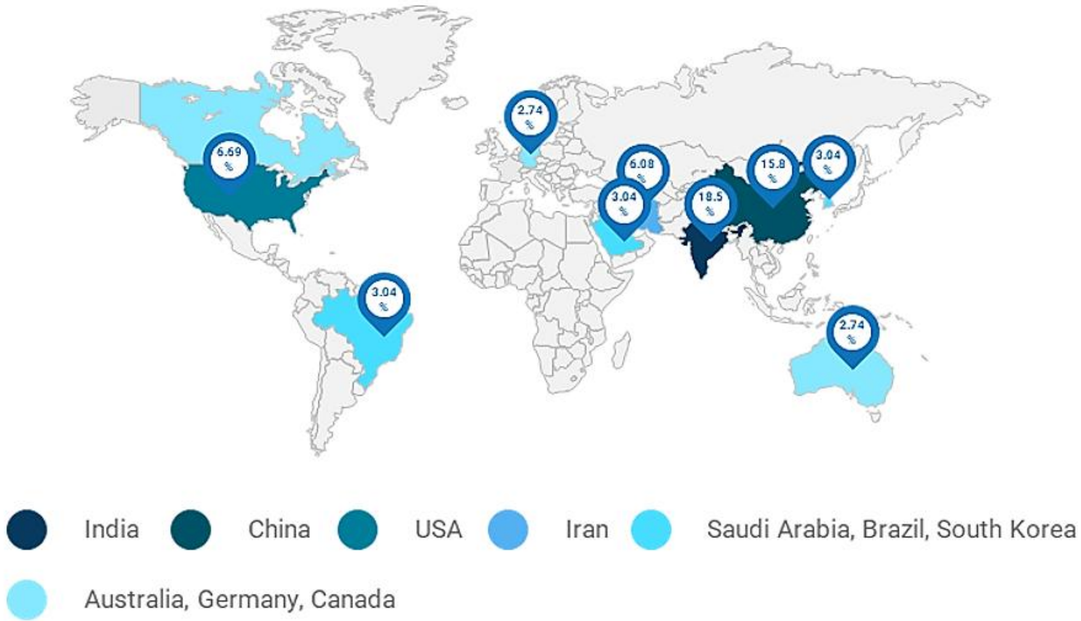

Figure 6. World map visualization of research activity due to countries.

India emerges as the dominant contributor with 61 publications (18.54% of the total), followed by China with 52 publications (15.81%) and the United States with 22 publications (6.69%), then Iran with 20 publications (6.08%), after that Saudi Arabia, Brazil, and South Korea with 10 publications (3.04%) for each, and finally, Australia and Germany with 9 publications (2.74%) for each and Canada as number 10 with 6 publications (1.82).

A slightly different image is presented when citation impact is considered instead of publication volume. Although China continues to dominate in total citations (2333), the average number of citations per publication is higher in Canada, Australia, and Saudi Arabia. This implies that even though these nations publish fewer works, their research often has a bigger impact on the field. Canadian publications have an average of 108.5 citations per manuscript, while Chinese publications have an average of 44.9.

International Collaboration Patterns

From Figure 5, we can see the United States appears as a central hub, forming strong collaborative ties with a wide range of countries, including Malaysia, Brazil, Germany, Canada, and South Korea. This suggests that the U.S. plays a strategic role in connecting research communities across different regions. Strong cooperation is also evident between China and India, two of the most active contributors in terms of publication output. China has close ties to Egypt, Germany, and Australia, whereas India frequently collaborates with Egypt, the US, and Germany. These nations do, however, typically have robust internal research ecosystems, and while their level of collaboration is considerable, it is frequently offset by high levels of domestic research output.

Increasingly, nations like South Korea and Saudi Arabia are participating in global research networks and building relationships with both Asian and Western partners. As a result of their intermediate geographic and scientific standing, notable nations like Iran and Turkey continue to have significant ties with both Eastern and Western collaborators. Although not specifically depicted in this figure, prior research suggests that smaller research economies, like Malaysia and Saudi Arabia, have higher Collaboration Intensity Index (CII) values (the ratio of internationally co-authored papers to total output), whereas countries with large domestic research bases, like China and India, typically have lower CII values.

This graphic emphasizes how international cooperation may raise the profile and influence of research. The general finding that globally co-authored research tends to garner more scientific attention and recognition is supported by the higher average number of citations per manuscript displayed by nations at the center of the network or those participating in cross-continental partnerships.

Journal Analysis

The bibliometric analysis of publication journals provides important information about the research dissemination structure for smart self-healing nanocoatings used in biomedical implants made of 316L stainless steel. Table 3 presents the top 10 journals based on the number of relevant papers listed in Scopus, thereby offering an open view of academic output and impact across publishing houses.

Table 3. Top 10 journals publishing documents in the field (2015–2025) based on Scopus data, including impact factor, H-index, and publisher.

Journal	No. of Document	No. of Citation	Impact Factor (IF)	H-index	Publisher
Materials Today: Proceedings	15	120	1.1	25	Elsevier
Journal of Alloys and Compounds	12	200	5.3	150	Elsevier
Materials Science and Engineering: C	10	180	6.2	130	Elsevier
International Journal of Biological Macromolecules	8	160	5.2	120	Elsevier
Journal of Materials Science	7	140	4.2	110	Springer
Journal of Biomedical Materials Research Part A	6	130	3.8	100	Wiley
Journal of Materials Research and Technology	5	110	4.5	90	Elsevier
Materials Chemistry and Physics	4	100	3.6	85	Elsevier
Journal of Applied Polymer Science	3	90	2.9	80	Wiley
International Journal of Molecular Sciences	2	80	4.6	70	MDPI

Materials Today: Proceedings stands out among the listed journals due to its biggest number of documents (15), which accounts for the majority of contributions in this field. However, despite its high volume of publications, the journal has a relatively low impact factor (1.1) and H-index (25), suggesting that although it serves as a convenient platform for conference-related and early-stage research, its long-term citation effect is limited.

In contrast, the Journal of Alloys and Compounds ranks second in terms of publication volume (12), but, with 200 citations, an impact factor of 5.3, and an H-index of 150, it has a remarkably strong impact profile. This implies that research published in this journal not only garners greater attention but also contributes more significantly to the scholarly conversation in the field of materials science. Similar to this, Materials Science and Engineering: C, which has 180 citations and 10 publications, has a high impact factor (6.2) and H-index (130), making it a crucial platform for research on biomaterials and cutting-edge coating technologies.

The interdisciplinary nature of this field of study is highlighted by journals that skillfully combine materials science with biomedicine, such as the International Journal of Biological Macromolecules and the Journal of Biomedical Materials Research Part A. Their impressive impact metrics and citation counts demonstrate their importance in addressing implant coatings' biological and functional performance.

Both Elsevier's Journal of Materials Research and Technology and Springer's Journal of Materials Science contribute significantly, offering a combination of strong bibliometric indicators and moderate document counts. These publications are prime examples of a well-rounded focus on materials engineering innovation and application. Interestingly, despite having fewer publications (three and two, respectively), the Journal of Applied Polymer Science and the International Journal of Molecular Sciences have comparatively high citation counts (90 and 80) and respectable impact factors (2.9 and 4.6), suggesting that some of their articles have had a significant impact, possibly due to their uniqueness or significance for polymer-based self-healing systems. Elsevier's dominance in the fields of materials and biomedical research is demonstrated by the fact that it distributes most of the top journals. Only three of the top ten journals,the International Journal of Molecular Sciences (MDPI), the Journal of Materials Science (Springer), the Journal of Biomedical Materials Research Part A, and the Journal of Applied Polymer Science (both Wiley),are published by other academic publishers. This suggests that publication efforts are concentrated in a small number of prominent scholarly houses.

The distribution of publications demonstrates a field of study that includes high-impact multidisciplinary journals and conference proceedings, among other publication priorities. Although productivity varies, peer-reviewed, application-focused research is typically prioritized in journals with greater impact factors and citation counts, especially in the fields of coatings, materials science, and biomedical engineering. This distribution illustrates how self-healing nanocoating research is developing, with both exploratory and thoroughly validated experiments finding a variety of distribution channels.

Notably, some journals contribute only one or two papers yet have a disproportionately high number of citations, whilst other journals appear regularly in the dataset with a significant number of documents. This suggests that certain individual publications have had a major influence on the subject even if they were published in less common settings. These instances imply that the impact of study depends not only on a journal's output on the subject but also on the originality and pertinence of individual contributions. Regardless of the journal's overall presence in the dataset, these highly cited papers in low-frequency journals demonstrate the significance of breakthrough discoveries and their capacity to influence future paths.

Document Types and Subject Area Analysis

Document Types Analysis

The distribution of document types, as illustrated in both the pie chart in Figure 7 and accompanying Table 4, provides valuable insight into the nature and maturity of research on smart self-healing nanocoatings for 316L stainless steel biomedical implants.

Table 4. Document types and their number of publications.

Document Type	Number of Document	% of All Publications
Article	105	44.30
Review	90	37.97
Book chapter	28	11.81
Book	12	5.06
Conference Paper	2	0.84

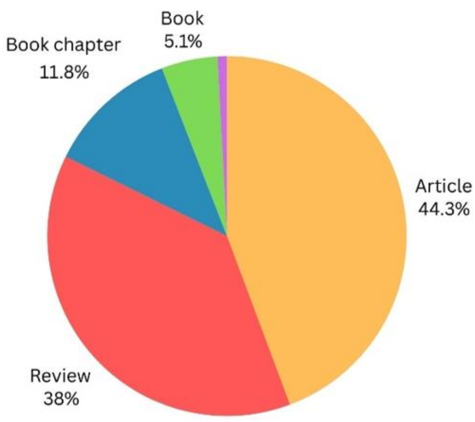

Figure 7. Distribution of publication types in the field, highlighting the percentage of articles, reviews, book chapters, and books.

According to the data, original research articles,which make up 44.3% of all publications (105 documents),dominate the field. New materials, coating techniques, and performance assessments are regularly introduced and validated in experimental and applied research, which is reflected in this. The large percentage of research articles indicates that the topic is developing rapidly, with ongoing contributions to new information, techniques, and technology.

Review articles, which comprise 38% of the publications (90 documents), come in close second. The large number of reviews suggests that the academic community is making an increasing effort to compile and assess the rising corpus of information. This is common in a new and multidisciplinary field of study where it is critical to compile results, spot patterns, and point out gaps in order to direct future research. A vital and reflective stage in the field's growth, when researchers are actively evaluating the advancements and potential paths of self-healing nanocoatings in biomedical settings, is also suggested by the abundance of reviews,nearly as many as original papers.

The fact that book chapters make up 11.8% of the total (28 documents) indicates that this subject is becoming more popular outside of journal publications and is being included in more general discussions in edited academic volumes and handbooks. The cross-cutting character of the topic encompassing materials science, nanotechnology, and biomedicine is further supported by the fact that these chapters most frequently offer theoretical background, foundational insights, or specialized debates inside multidisciplinary publications. Books make up 5.1% (12 documents) of the dataset, on the other hand. Even though it is a smaller percentage, this shows a level of maturity where some academics or organizations are compiling a wealth of information on the topic into edited volumes or monographs, possibly providing thorough summaries or specialized treatments of subtopics like corrosion mechanisms, bioactive materials, or the synthesis of nanocoatings.

Finally, conference papers make up a pitiful 0.8% of the publications (2 documents). This low number implies that official peer-reviewed routes, rather than early conference proceedings, are the main means of disseminating research in this field. It might also be a reflection of the field's applied and biological focus, which lessens the need for conference-based dissemination by requiring complete experimental validation and regulatory relevance for publishing.

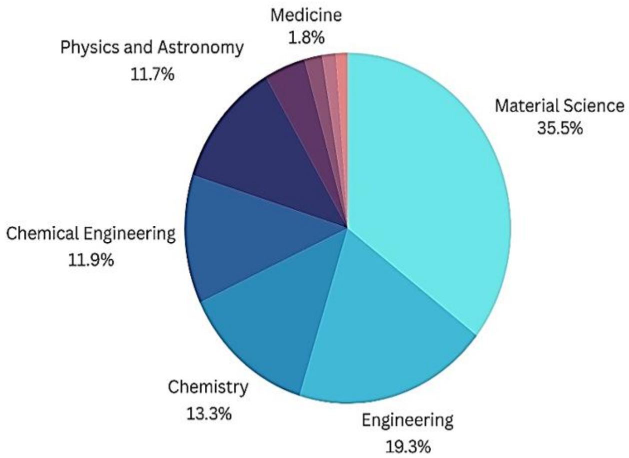

Figure 8. Most subject area published in the field

Subject Area Analysis

Research on smart self-healing nanocoatings for 316L stainless steel biomedical implants is intrinsically interdisciplinary, as evidenced by the topic area distribution in Figure 8's pie chart. The fact that certain papers are indexed under two or more subject categories is significant because it illustrates the field's broad reach, which extends from applied biomedical engineering to basic material science. With 35.5% of the papers (182 documents), Materials Science is in the lead, highlighting the fundamental role of coating technologies, surface modification, and nanomaterials. With 19.3%, engineering comes in second, emphasizing the components of coating design, production, and performance assessment for practical biomedical applications.

The relevance of synthesis techniques, corrosion mechanisms, and the creation of functional materials is reflected in the substantial shares held by Chemistry (13.3%) and Chemical Engineering (11.9%). Through analytical and characterization methods that are crucial for assessing coating structure and healing performance, physics and astronomy (11.7%) provide a contribution. Subject areas including biochemistry, genetics and molecular biology (21 documents) and medicine (9 documents), despite being less well-known, indicate an increasing biomedical focus, especially for evaluating in vitro/in vivo performance and biocompatibility. Emerging and specialized applications are captured by other disciplines, including environmental science and multidisciplinary sciences. Although materials science is the main focus of this field of study, the overlap with other fields validates the need for an integrated strategy in order to create and assess smart coatings appropriate for biological settings.

Keywords Analysis

Keywords provide valuable insights into the core themes and research focuses within a field. Table 5 presents the most frequently occurring author keywords in the dataset, along with their occurrence frequency and percentage.

Table 5. The most frequently occurring author keywords in the dataset

Keyword	Frequency	% of All Publications
Corrosion	39	16.53
Corrosion resistance	24	10.17
Biocompatibility	21	8.9
Coating	18	7.63
Coatings	17	7.2
Hydroxyapatite	16	6.78
Surface modification	15	6.36
Corrosion protection	14	5.93
Biomaterials	14	5.93
Biomedical applications	12	5.08
Bioactivity	10	4.24
Chitosan	10	4.24
Magnesium alloy	9	3.81
Tissue engineering	9	3.81
Magnesium alloys	8	3.39

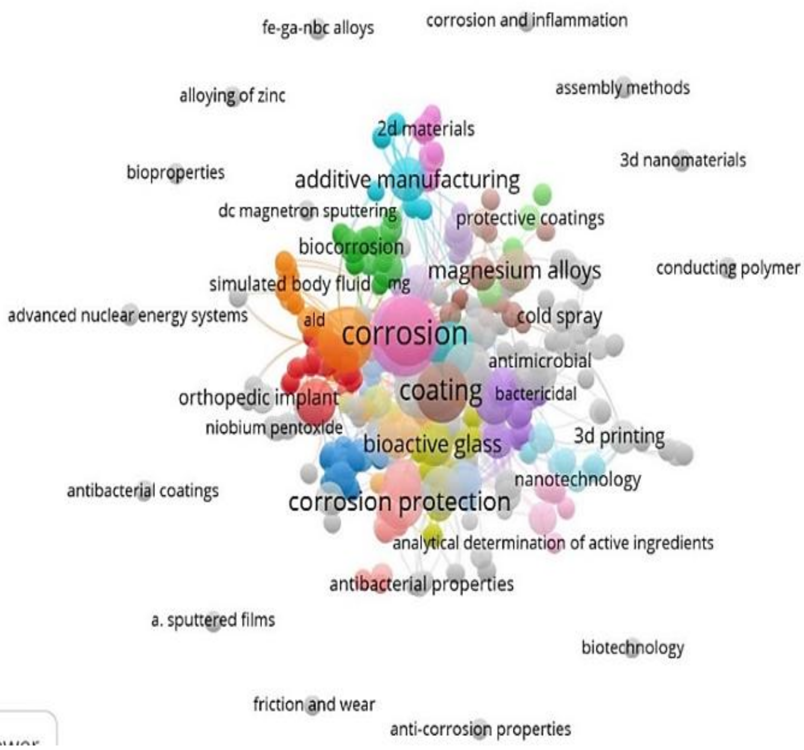

Figure 9. Co-occurring keyword network illustrating thematic clusters and research trends in the field

Important information on the topic structure and research focus in the area of smart self-healing nanocoatings for 316L stainless steel implants may be found in the keyword frequency table and visualization map in Figure 9. The most common and related phrases in the VOSviewer network, as illustrated in Figure 9, are "corrosion," "coating," "corrosion resistance," and "biocompatibility",all of which are essential to the operation and biomedical significance of protective surface layers. This is graphically supported by Table 5, which shows that the term "corrosion" appears in 16.5% of all papers, followed by "coating" (7.6%), "corrosion resistance" (10.2%), and "biocompatibility" (8.9%). The continuous emphasis on improving the biological performance of coated implants is reflected in other often used words, such as "hydroxyapatite," "surface modification," and "bioactivity."

Although the idea of self-healing coatings is mentioned in the literature, less than 0.84% of targeted studies now use it. This implies that before thoroughly investigating sophisticated self-healing capabilities, the majority of scientists are still attempting to resolve basic issues like long-lasting corrosion prevention and making sure implants adhere to bone tissue. The results show that this discipline is still based on fundamental materials science ideas, with researchers laying solid groundwork in biological safety and durability. The lack of focus on self-healing mechanisms indicates unrealized promise as well as the need for greater multidisciplinary research that combines advances in biomedical engineering and materials innovation. We might anticipate a greater emphasis on "smart" coatings,those that actively maintain themselves while promoting the formation of healthy tissue,as fundamental performance criteria are better understood.

Top Papers in the Field

The citation analysis of the top 10 most-cited papers within the dataset shown in Table 6 reveals significant contributions shaping the field of smart protective coatings and related biomedical applications.

Table 6. Top 10 most-cited papers in the dataset, ranked by total citation count and their percentage share of overall citations.

Paper Title	Citations	% of Total Citations
Recent developments and applications of protective silicone coatings: A review of PDMS functional materials	531	7.28
Additive manufacturing of metallic lattice structures: Unconstrained design, accurate fabrication, fascinated performances, and challenges	381	5.23
Polydopamine antibacterial materials	376	5.16
Calcium orthophosphate deposits: Preparation, properties and biomedical applications	24/7	3.39
Protective polymeric films for industrial substrates: A critical review on past and recent applications with conducting polymers and polymer composites/nanocomposites	239	3.28
Tissue Engineering and Regenerative Medicine: Achievements, Future, and Sustainability in Asia	200	2.74
A review on the corrosion behaviour of nanocoatings on metallic substrates	166	2.28
A critical review on functionally graded coatings: Methods, properties, and challenges	128	1.76
Superhydrophobic surfaces and coatings by electrochemical anodic oxidation and plasma electrolytic oxidation	124	1.7
Chitosan, its derivatives and composites with superior potentials for the corrosion protection of steel alloys: A comprehensive review	120	1.65

With 531 citations, or 7.28% of all citations, the highly influential review "Recent developments and applications of protective silicone coatings: A review of PDMS functional materials" by Eduok et al. (2017) tops the list, demonstrating its fundamental role in directing future research on functional coating systems. The interdisciplinary fusion of materials engineering, biology, and surface science is reflected in other high-impact studies on polydopamine antibacterial materials (5.16%) by Fu et al. (2021) and additive manufacturing by Chen et al. (2021) (5.23%). The significance of literature synthesis in this developing field is highlighted by the notable number of review papers that make it to the top tier, including those that concentrate on conducting polymers, functionally graded coatings, and nanocoatings. The relevance of biopolymers in corrosion-resistant biomedical coatings is highlighted in a particularly pertinent study for this topic, "Chitosan, its derivatives, and composites with superior potentials for the corrosion protection of steel alloys," by Ashassi-Sorkhabi and Kazempour (2020) which has gained 120 citations (1.65%). According to the citation landscape, biocompatible and corrosion-protective techniques are receiving more attention, even though comprehensive reviews and advanced materials themes still have the most scholarly impact. The fact that research specifically on self-healing is not included in the list of the most referenced, however, is noteworthy and confirms that this subtopic is still underrepresented in high-impact publications.

In Vitro vs. In Vivo Experimentation

The data set makes it clear that a generous portion of the experimental effort is still in vitro. We looked for specific references to "in vivo" or "in vitro" research in the titles, abstracts, and keywords. Of the 105 published articles, 88 reports doing in vitro experiments, 13 reports conducting in vivo investigations, and 4 reports concentrating on predictive modeling or computational simulations. Remarkably, only six of those studies conducted testing solely in vivo; roughly seven of those papers had both in vitro and in vivo components. These numbers imply that many studies on self-healing implant covering have been carried out in vitro, that is, in a laboratory setting employing cell cultures, simulated bodily fluids, or controlled chamber tests. In this context, "in vitro" often refers to testing coated steel samples under physiologically simulated conditions. For instance, coating steel coupons can be submerged in phosphate-buffered saline or Simulated Body Fluid (SBF) to see corrosion and healing, or mammalian cells can be seeded on the coated surface to evaluate biocompatibility. Only a small number of the publications advanced to in vivo animal testing, according to the statistics. A few studies, for example, discuss implanting coated steel disks or pins into rats or rabbits to track the body's corrosion and integration over time, although these are rather uncommon. A translational gap is highlighted by this bias toward vitro work: although numerous coatings exhibit encouraging self-healing and anticorrosion properties in lab simulations, significantly less have been confirmed in vivo.

It makes sense because in vivo investigations are more costly, time-consuming, and need ethical approval. However, the small number of vivo investigations says that most researchers have concentrated on fundamental lab characterization and material development. To make connections and understand the healing process both before and after implantation, many studies that do incorporate in vivo tests nonetheless combine them with in vitro analysis. In this subject, in vitro testing is almost widespread, while in vivo demonstrations are still in the initial stages of research. This suggests that as technology advances, more animal models and eventually clinical assessments will be needed.

Conclusion

From 2015 to 2025, this study offers a thorough bibliometric overview of the state of research on smart self-healing nanocoatings for biomedical implants made of 316L stainless steel worldwide. The results show a distinct increase trend in the number of publications, particularly after 2020, which can be attributed to developments in nanotechnology, materials science, and biomedical engineering. While in vivo and computational studies are still scarce, in vitro research on corrosion prevention and biocompatibility dominates the field. The term "self-healing" is used in comparatively few articles despite increased interest, indicating that although the idea exists, its use in biomedical coatings is still in its infancy. Countries like China and India produce a large number of publications, whereas Canada and Australia have the highest citation impact per article. According to the journal distribution, the most significant research frequently originates from less common sources, even when many papers are published in high-output venues.

Although the area is led by a core group of researchers, author and institutional partnership maps show increasing international interaction. Furthermore, a large research gap is highlighted by the dearth of comprehensive in vivo investigations and real-world testing, since many studies are still focused on basic lab-scale evaluations. According to the findings, further multidisciplinary research is required to combine clinical performance with self-healing capabilities. Creating more intelligent coatings that can react and adapt to the physiological environment will be crucial as the need for durable, secure, and effective biomedical implants grows. For scholars, stakeholders, and funding organizations looking to further this exciting field, this report provides insightful guidance.

Recommendations

Future research should concentrate on going beyond in vitro studies by incorporating more in vivo experiments that replicate actual physiological settings in order to expedite advancements in this sector. One major issue that still has to be investigated is the development of long-term, biocompatible, non-toxic healing agents. The design and performance predictions of self-healing systems under various biological situations may be improved by combining machine learning, predictive modeling, and computational simulation.In order to provide a more comprehensive picture of worldwide research activity and to identify new trends, partnerships, and research gaps, bibliometric studies could also broaden their coverage by integrating other databases, such as Web of Science, Dimensions, or PubMed. These actions will help develop self-healing nanocoatings for next-generation biomedical implants that are more efficient, intelligent, and therapeutically feasible.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility for the content of this article published in the EPSTEM journal belongs entirely to the authors.

* This study does not involve any human or animal subjects and therefore did not require ethics committee approval.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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